Peculiar debris disks from Herschel/DUNES

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in collaboration with the
HERSCHEL/DUNES team

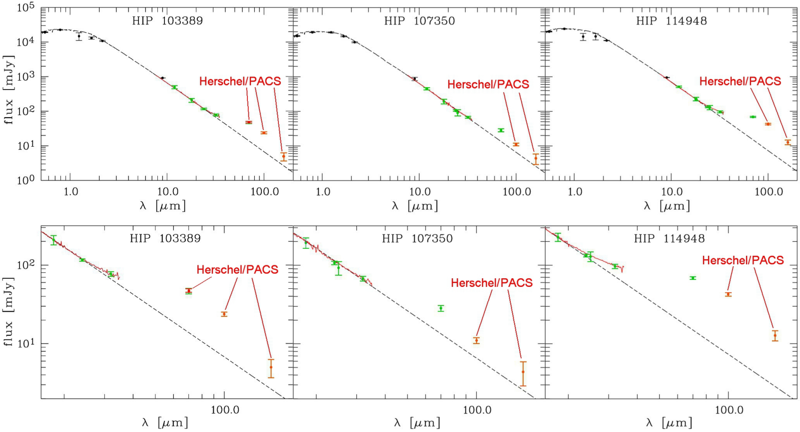
using HERSCHEL/DUNES data

The stars

Stellar properties

Object	HIP 103389	HIP 107350	HIP 114948
d [pc]	22.0	17.9	20.5
Spectral type	F7 V	G0 V	F7 V
L [$\mathrm{L}_\odot$]	2.03	1.09	1.87
T_{eff} [K]	6257	5952	6240
Age [Myr]	250	330	250

SEDs


HIP 103389
HIP 107350
HIP 114948
Herschel/PACS
flux [mJy]
λ [μm]
10^0
10^1
10^2
10^3
10^4
10^5
1.0
10.0
100.0

Treating the dust as a single temperature black body

Planck's law:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp\left[hc/\lambda kT\right] - 1}$$

Spectral index Δ:

$$\Delta = \frac{\partial \log F_\lambda}{\partial \log \lambda} \qquad \Delta_{\lambda_1,\lambda_2} = \frac{\log F_{\lambda_2} - \log F_{\lambda_1}}{\log \lambda_2 - \log \lambda_1}$$

Rayleigh-Jeans regime: $\Delta = -2$, steeper would mean $\Delta < -2$

More exact treatment of the disk

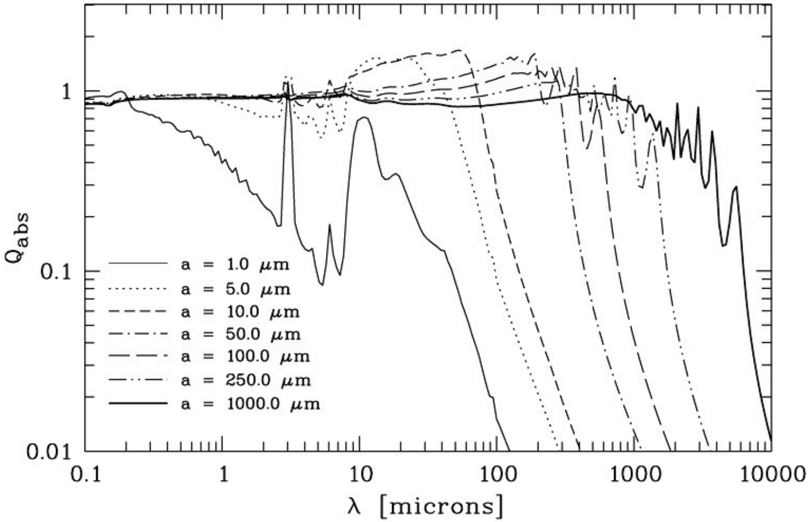
Two (or more) single temperature black bodies

Same result, $\Delta = -2$ where Rayleigh-Jeans approximation valid for coldest dust component

Mie theory

$$B'_\lambda(T) = Q_{\mathrm{abs}}(\lambda) \cdot \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp\left[hc/\lambda kT\right] - 1}$$

Absorption efficiency of dust



So why are there any "unusually steep" SEDs?

- Dust radially distributed (range of temperatures)
- Different grain sizes (range of temperatures, breaks in Q_{abs} at different wavelengths)
- Larger grains ($a > 50\,\mu\mathrm{m}$) behave similar to black body ($Q_{\mathrm{abs}} \approx 1$) up to $\lambda \approx 300\,\mu\mathrm{m}$

$\Longrightarrow$ Breaks in SED smoothened, shifted towards long wavelengths

- SEDs that fall of steeper than Planck's law at wavelengths $\approx 100\,\mu\mathrm{m}$ have never been observed before

So what is an "unusually steep" SED?

$$\boxed{\Delta_{\lambda_1,\lambda_2} < -2}$$

- At any wavelength combination (70 μm, 100 μm, 160 μm)
- Including error bars

Our disks

Object	HIP 103389	HIP 107350	HIP 114948
$\Delta_{70/100}$	1.94 ± 0.32	2.66 ± 0.45	1.35 ± 0.26
$\Delta_{100/160}$	3.31 ± 0.69	1.95 ± 0.88	2.57 ± 0.44
$\Delta_{70/160}$	2.72 ± 0.39	2.25 ± 0.53	2.04 ± 0.22

A simple debris disk model

The challenge

- Only few relevant SED measurements (up to 8)
- No resolved data (only upper limits, since not resolved with PACS)
- Somehow "strange" results expected

Spatial dust distribution

- Power law $n(R) \propto R^{-\alpha}$
- R_{in}, R_{in}

Grain size distribution

- Power law $n(a) \propto a^{-\gamma}$
- a_{min}, a_{max}

Three different approaches

Approach 2

Steep size distribution

- $a_{\max} = 1\,\mathrm{mm}$
- $\alpha = 0.0$
- Others free

$\Longrightarrow$ Steep grain size distribution

$\Longrightarrow$ Large lower grain size (several μm)

$\Longrightarrow$ Narrow rings at few tens of AU

Approach 3

Force standard values

- $a_{\max} = 1\,\mathrm{mm}$
- $\gamma = 3.5$
- $\alpha = 0.0$

$\Longrightarrow$ Unsatisfactory fit, large χ^2

$\Longrightarrow$ Still too large lower grain size

$\Longrightarrow$ Narrow rings at few tens of AU

Approach 4

Free upper grain size

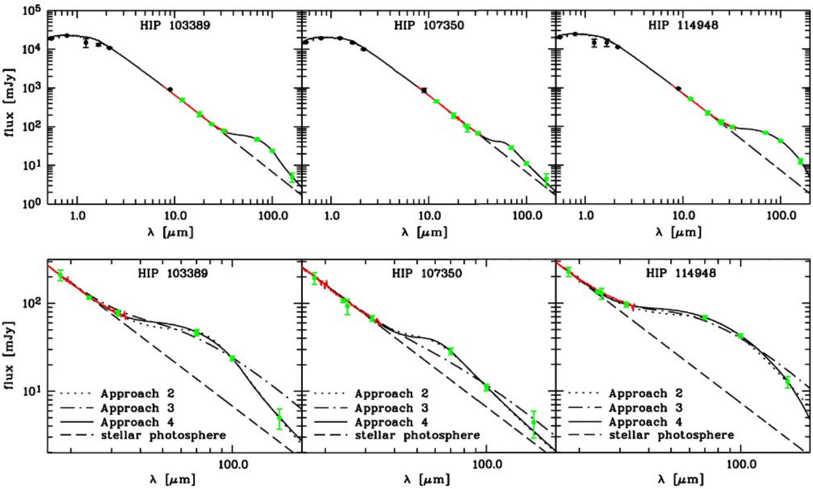
- $a_{\max}$ free
- $\gamma = 3.5$
- $\alpha = 0.0$

$\Longrightarrow$ Small upper grain size

$\Longrightarrow$ Large lower grain size (several μm)

$\Longrightarrow$ Narrow rings at few tens of AU

SED best-fits with SAnD (Kiel)

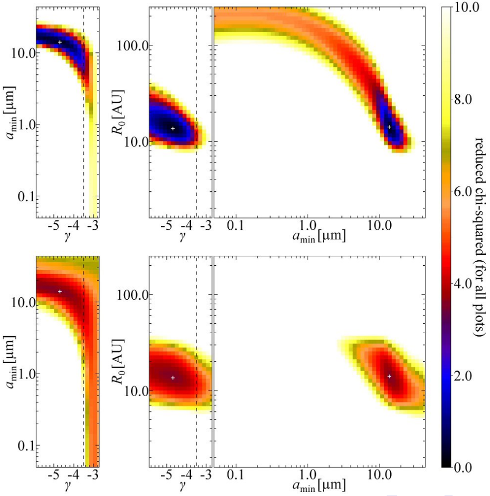


Including spatial constraints with GRaTeR (Grenoble)

HIP 114948

without profile:

with profile:



Results

- Strong under abundance of large ($>$ few tens of micron) grains
- Ringlike shape of the disks preferred over broad disks, but not very significant
- Distance from the star of few tens of AU

Scenario 1: Deviation from a standard equilibrium collisional cascade?

- Grain size distribution following $\gamma = -3.5$ only valid for “standard equilibrium collisional cascade”
- No drag forces, grain sizes from 0 to ∞
- Good approximation for massive disks where collision time scales very short
- Here very low disk mass, maybe even close to transport dominated

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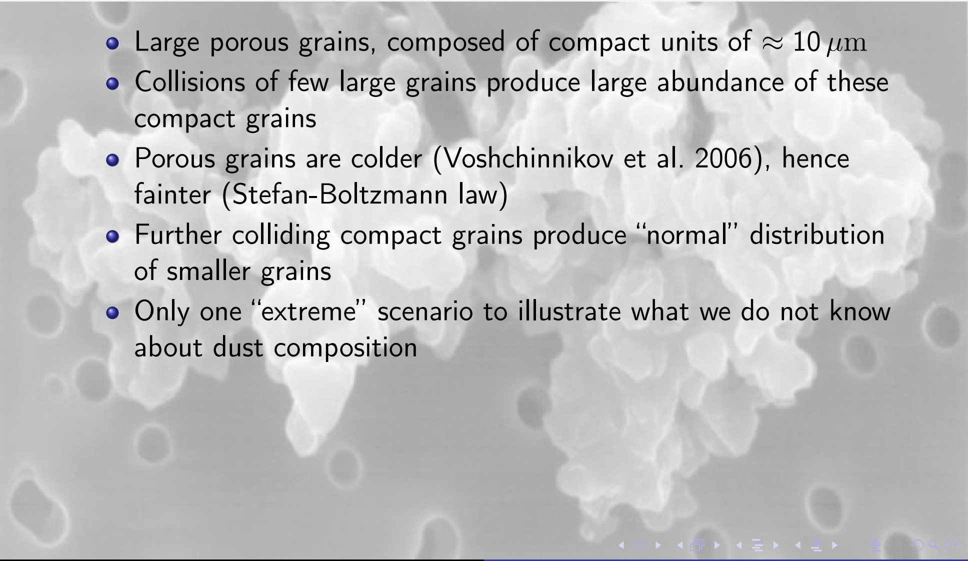
☺ Wavy size distributions, steep in the relevant range possible

☺ Large lower grain size than blow-out size possible

Scenario 2: Different grain composition?



- Large porous grains, composed of compact units of $\approx 10\,\mu\mathrm{m}$
- Collisions of few large grains produce large abundance of these compact grains
- Porous grains are colder (Voshchinnikov et al. 2006), hence fainter (Stefan-Boltzmann law)
- Further colliding compact grains produce “normal” distribution of smaller grains
- Only one “extreme” scenario to illustrate what we do not know about dust composition

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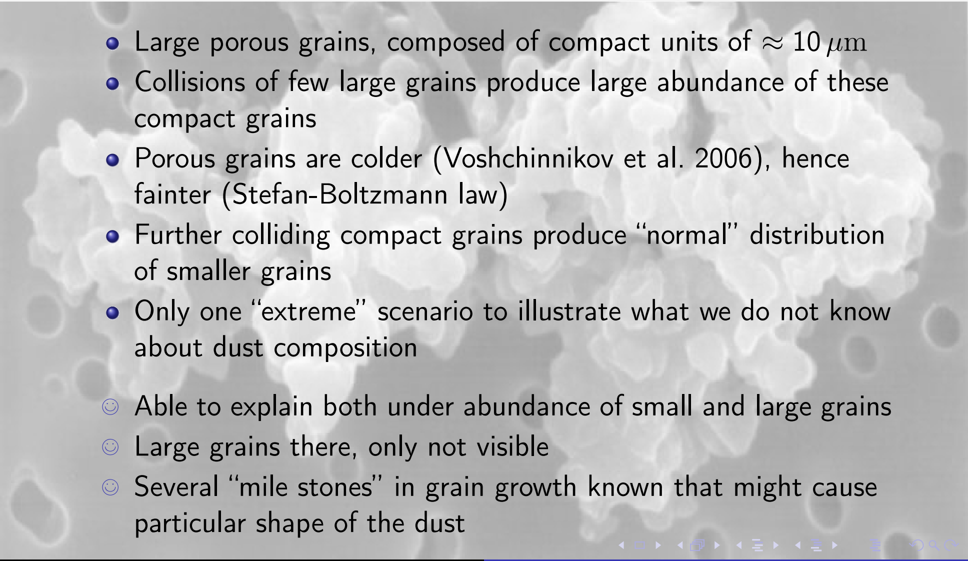

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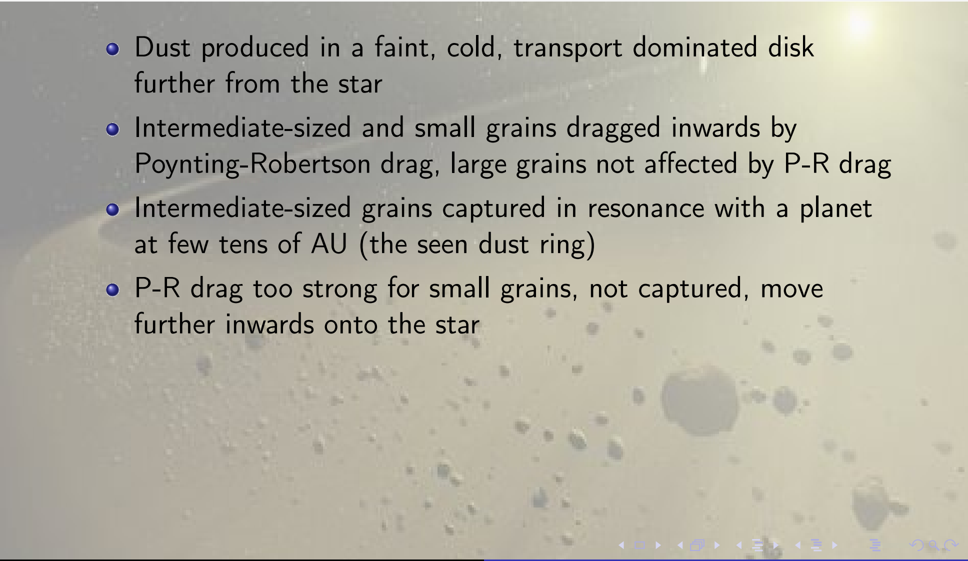
- ☺ Able to explain both under abundance of small and large grains
- ☺ Large grains there, only not visible
- ☺ Several "mile stones" in grain growth known that might cause particular shape of the dust

Scenario 3: A shepherding planet



- Dust produced in a faint, cold, transport dominated disk further from the star
- Intermediate-sized and small grains dragged inwards by Poynting-Robertson drag, large grains not affected by P-R drag
- Intermediate-sized grains captured in resonance with a planet at few tens of AU (the seen dust ring)
- P-R drag too strong for small grains, not captured, move further inwards onto the star

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☺ Able to explain both under abundance of small and large grains

☺ Large grains there, only not visible

☺ No further stuff needed like porous grains & a mechanism to produce very special grains

Future observational perspectives

Source	$L_{\mathrm{dust}}/L_{\mathrm{star}}$	$(F_{\mathrm{dust}}/F_{\mathrm{star}})_{0.6\,\mu\mathrm{m}}$		$(F_{\mathrm{dust}}/F_{\mathrm{star}})_{2.2\,\mu\mathrm{m}}$	
		face-on	edge-on	face-on	edge-on
HIP 103389	1.5×10^{-5}	1.1×10^{-6}	1.9×10^{-4}	1.8×10^{-6}	1.5×10^{-4}
HIP 107350	0.6×10^{-5}	4.9×10^{-7}	7.4×10^{-6}	6.9×10^{-7}	3.9×10^{-5}
HIP 114948	2.5×10^{-5}	2.1×10^{-6}	3.4×10^{-4}	3.7×10^{-6}	2.6×10^{-4}

- Too faint for optical/near-infrared direct imaging, extension too small for coronagraphy
- SED decreasing quickly towards long wavelengths, too faint for ALMA continuum observations
- Optical/near-infrared interferometry: VLTI/PIONIER - FOV too small for face-on orientation, edge-on possible, but sensitivity probably too low
- Further photometry and spectroscopy: $35\,\mu\mathrm{m}$ – $200\,\mu\mathrm{m}$ interesting (Herschel/PACS spectroscopy, SOFIA photometry)
- Optical/near-infrared search for planetary companions possible, very interesting if Scenario 3 is correct

SAnD SED fitting results

	HIP 103389					
	Approach 2		Approach 3		Approach 4	
	silicate	silicate + ice	silicate	silicate + ice	silicate	silicate + ice
$R_{\rm in}$ [AU]	18.2 [7.9 – 24.5]	20.9 [8.0 – 26.6]	11.9 [4.2 – 16.0]	13.6 [4.4 – 19.1]	42.3 [12.9 – 63.3]	22.5 [8.6 – 43.0]
$R_{\rm out}$ [AU]	20.0 [16.3 – 65.1]	20.9 [17.3 – 77.3]	12.0 [8.8 – 37.4]	13.6 [10.2 – 38.5]	46.0 [21.3 – 138.5]	22.5 [17.9 – 110.9]
α	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)
$a_{\rm min}$ [μm]	9.5 [7.8 – 10.4]	12.8 [10.7 – 13.6]	6.1 [2.8 – 9.8]	6.6 [2.6 – 12.0]	4.2 [3.1 – 7.8]	9.3 [3.7 – 14.9]
$a_{\rm max}$ [μm]	1000.0 (fixed)	1000.0 (fixed)	1000.0 (fixed)	1000.0 (fixed)	14.3 [12.7 – 18.1]	22.7 [14.3 – 28.5]
γ	7.4 [6.3 – 10.0]	9.0 [6.5 – 10.0]	3.5 (fixed)	3.5 (fixed)	3.5 (fixed)	3.5 (fixed)
$M_{\rm disk}$ [$M_\odot$]	3.89e-11	3.87e-11	1.41e-10	1.21e-10	1.46e-10	4.35e-11
reduced χ^2	0.816	0.776	10.277	8.488	0.628	0.760

	HIP 107350					
	Approach 2		Approach 3		Approach 4	
	silicate	silicate + ice	silicate	silicate + ice	silicate	silicate + ice
$R_{\rm in}$ [AU]	29.1 [7.9 – 47.2]	30.6 [5.6 – 44.1]	9.6 [3.0 – 15.6]	10.9 [3.0 – 16.5]	37.1 [4.3 – 54.4]	35.2 [7.2 – 54.2]
$R_{\rm out}$ [AU]	31.3 [13.9 – 113.9]	32.3 [16.0 – 138.5]	9.6 [5.8 – 33.0]	11.0 [9.1 – 35.7]	37.4 [19.2 – 187.5]	35.2 [17.4 – 145.3]
α	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)
$a_{\rm min}$ [μm]	6.9 [2.7 – 10.9]	8.2 [3.6 – 10.7]	5.7 [4.8 – 11.0]	5.8 [4.9 – 11.7]	7.8 [1.6 – 10.4]	9.6 [2.2 – 13.5]
$a_{\rm max}$ [μm]	1000.0 (fixed)	1000.0 (fixed)	1000.0 (fixed)	1000.0 (fixed)	7.8 [6.3 – 13.3]	9.6 [6.4 – 17.4]
γ	10.0 [6.0 – 10.0]	10.0 [5.9 – 10.0]	3.5 (fixed)	3.5 (fixed)	3.5 (fixed)	3.5 (fixed)
$M_{\rm disk}$ [$M_\odot$]	3.33e-11	2.79e-11	3.16e-11	2.73e-11	4.64e-11	3.25e-11
reduced χ^2	1.652	1.568	4.229	3.869	1.528	1.488

	HIP 114948					
	Approach 2		Approach 3		Approach 4	
	silicate	silicate + ice	silicate	silicate + ice	silicate	silicate + ice
$R_{\rm in}$ [AU]	12.8 [7.1 – 13.7]	13.5 [7.8 – 14.9]	12.7 [5.5 – 16.6]	14.0 [7.9 – 19.1]	32.5 [9.0 – 40.1]	13.3 [8.4 – 14.5]
$R_{\rm out}$ [AU]	12.8 [12.1 – 23.2]	13.8 [12.9 – 24.9]	12.7 [10.5 – 25.6]	14.1 [11.0 – 30.8]	34.5 [26.9 – 81.4]	13.8 [12.9 – 22.9]
α	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)
$a_{\rm min}$ [μm]	9.6 [8.9 – 10.2]	12.9 [11.9 – 13.8]	6.4 [3.6 – 9.9]	7.4 [3.0 – 11.7]	3.2 [2.6 – 4.6]	11.8 [10.7 – 13.1]
$a_{\rm max}$ [μm]	1000.0 (fixed)	1000.0 (fixed)	1000.0 (fixed)	1000.0 (fixed)	24.2 [10.0 – 27.3]	43.8 [10.0 – 53.2]
γ	4.7 [4.4 – 5.2]	4.7 [4.4 – 5.1]	3.5 (fixed)	3.5 (fixed)	3.5 (fixed)	3.5 (fixed)
$M_{\rm disk}$ [$M_\odot$]	6.57e-11	6.48e-11	2.65e-10	2.21e-10	1.78e-10	4.85e-11
reduced χ^2	0.284	0.232	3.291	2.333	0.132	0.232

Thank you very much!